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## A MICRO MOBILE MECHANISM USING THERMAL EXPANSION AND ITS THEORETICAL ANALYSIS

-- A comparison with Impact Drive Mechanism using piezoelectric elements --

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### ABSTRACT

Thermal expansion of solid materials can be used as an actuating mechanism for micro machines. It produces as much displacement as piezoelectric elements, but has the problem of response speed for ordinary scale machines. While, actuators using thermal expansion have the possibility of fast response if their sizes are small because of their high heat emission ratio. In addition it has the advantages of: (1) Simple actuator structure and easy fabrication process, (2) Various materials can be adopted for actuator, (3) Able to operate in high temperature and in vacuum, (4) Remote control by supplying heat with laser beam or RF electromagnetic wave. This paper introduces a micro motion mechanism driven by thermal expansion and then introduces a theoretical analysis on a motion mechanism using thermal expansion. In addition, a comparison with a piezoelectric element illustrates the characteristics of the actuator. A basic experiment using electric current heating type actuator shows the possibility of the thermal expansion actuator.

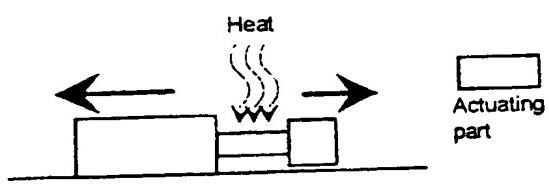
### INTRODUCTION

Thermal expansion is thought to be insufficient for actuation for ordinary size mechanisms because of its small displacement and slow response. But the response speed can be improved in micro machine due to the high heat emission speed that comes from scale effect. There have

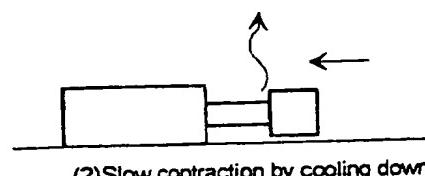
been a number of reports on vibration excitation using thermal energy.[1] In this paper, an application of thermal extension to Impact Drive Mechanism is discussed about. This method is based on the same principle as the Impact Drive Mechanism, which the authors have been developed and reported in MEMS-90.[2] It utilizes reactional force caused by rapid displacement of thermal expansion. Then a theoretical analysis and experimental result are given to demonstrate the ability of thermal expansion. A comparison with the Impact Drive Mechanism using piezoelectric element is given to illustrate characteristics and advantages of the thermal expansion actuator. At the end, applications of this actuator will be mentioned to.

### PRINCIPLE OF MOTION

The motion of the mechanism is carried out in the similar way with the Impact Drive Mechanism using piezoelectric element. Its fundamental idea is to utilize static friction and inertial force. Fig.1 illustrates the mechanism. The motion mechanism consists of a main body, an actuating part, and a weight. The main body lies on a guide surface and is held by static friction acting between them. At one end of the main body, the actuating part is attached. It expands laterally when given thermal energy. At the other end of the actuating part, a weight is attached. The actuating part expands to accelerate the weight and an impulsive inertial force is generated to move the main body. The motion is carried out in three steps.

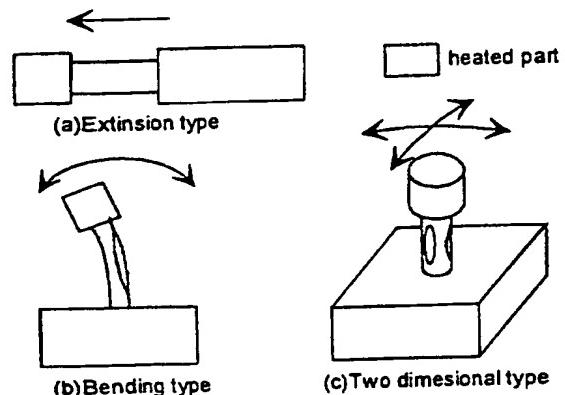


(1)Rapid extension by heat

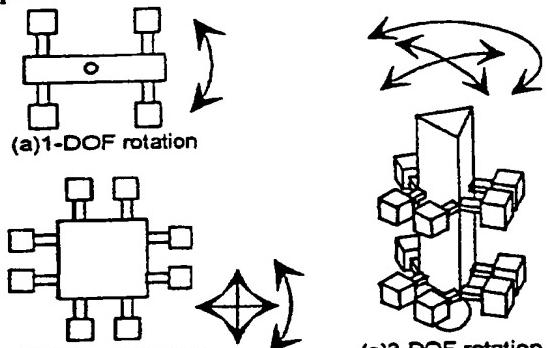


(2)Slow contraction by cooling down

**Fig.1 Principle of Motion**

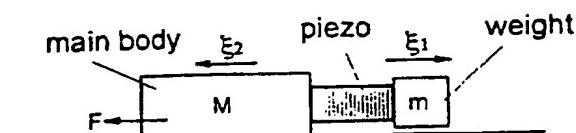
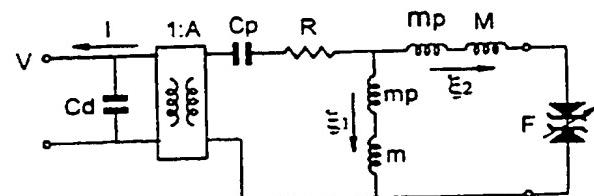


**Fig.2 Examples of configuration of actuating parts**

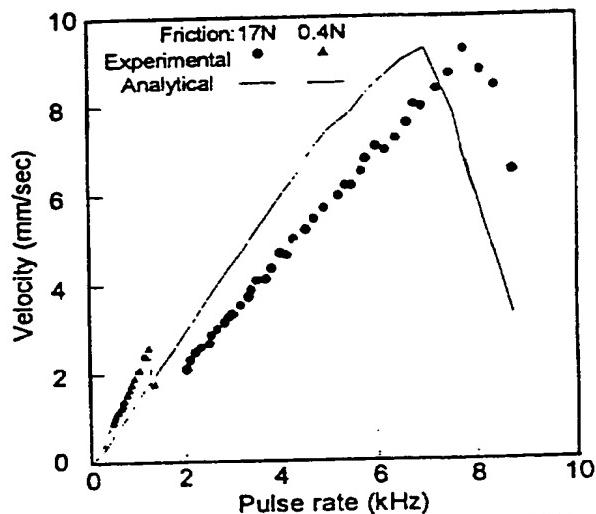


**Fig.3 Applications to multiple degree-of-freedom mechanisms**

- (1)The temperature of the actuating part is same as the atmosphere and the main body is stopped.
- (2)Thermal energy is given to the actuating part and it causes rapid extension to generate impulsive force. The main body moves left against static friction.



**Fig.4 An equivalent circuit for Analyzing Impact Drive Mechanism using piezoelectric elements**



**Fig.5 A result of the analysis on Impact Drive Mechanism (Driving pulse rate and velocity—comparison between analytical and experimental result)**

(3)The actuating part is cooled down. Since the cooling down is much slower than heating, the inertial force generated by the contraction of the actuating part is smaller than the static friction. As a result, the main body keeps its position.

The main body can make long distance motion repeating these cycles from (1) to (3). The step size of the motion can be controlled by the amount of thermal energy given to the actuating part in step (2).

#### Configuration of motion mechanism

Several types of actuating part and heating method are possible. Fig.2 shows examples of configuration of the actuating part. (a) is the simple extension type that the authors adopted for experimental setup. (b) is bending

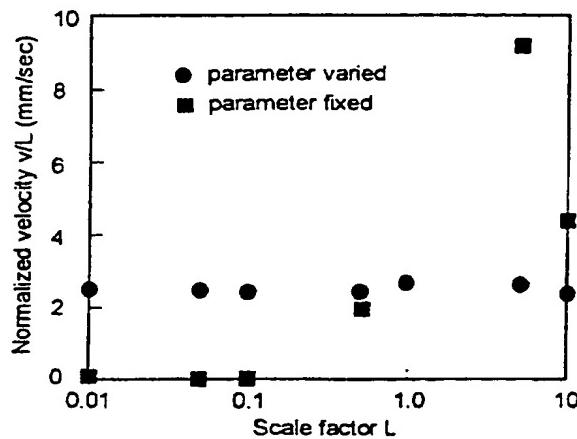


Fig.6 A result of calculation showing step size of motion of the Impact Drive Mechanism using piezoelectric element as a function of size of the mechanism.

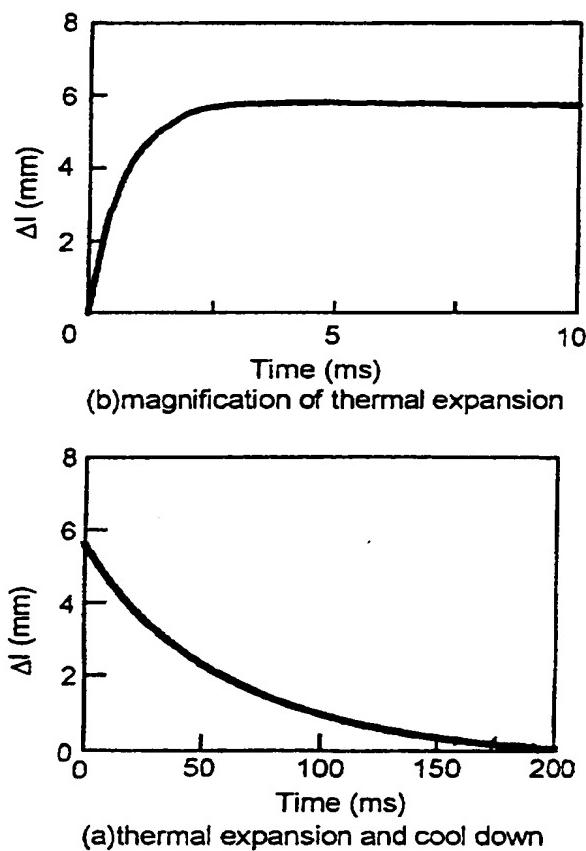


Fig. 7 Displacement by numerical calculation

motion type. The thermal energy is given to one side of the actuator. The direction of motion can be switched by the change of the side to heat, while the (a) type cannot change the motion direction. (c) type shows a multiple

degrees-of-freedom actuating part. The bending motion is controlled by the position to be heated. Fig.3 also shows examples of motion mechanisms with various mechanical degrees of freedom. In addition to a simple linear motion mechanism, rotational motion, XY motion,  $XY\Theta$  motion, three degree-of-freedom rotating motion is possible. This is a fundamental advantage of the Impact Drive Mechanism, which utilizes inertial force and friction. A variety of materials can be used for actuating part except for some special low thermal expansion coefficient ones. This gives a great advantage for manufacturing micro machines.

Several methods are possible for rapid heating of the actuating part. For example, electric current, laser lights, RF electromagnetic wave, direct heat transfer, chemical heating and so on. Among these methods, laser lights and electromagnetic wave are advantageous methods because they can transmit heat energy without any wire connection.

#### IMPACT DRIVE MECHANISM USING PIEZOELECTRIC ELEMENTS

The authors have developed a micro positioning mechanism using piezoelectric element and have given a report in MEMS-90.<sup>[2]</sup> Since the Impact Drive Mechanism utilizes frictional force, large friction of micro machines may cause a great problem. But a recent analysis on Impact Drive Mechanism shows that a micro sized Impact Drive Mechanism can operate against large friction even the size of the mechanism is small.<sup>[3]</sup> Fig.4 shows an equivalent circuit for an Impact Drive Mechanism using piezoelectric elements. The analysis was carried out using this equivalent circuit and the characteristics of the Impact Drive Mechanism including the effect of the driving parameters, motion speed, and payload capacity. The result of analysis was in good agreement with the experimental result.<sup>[4]</sup> Fig.5 shows one of these results that explains the relationship between velocity and the pulse rate for different frictional force. Experimental results are indicated by dots and triangles and results of calculation are indicated by lines. The maximum speed of 9.5mm/s is obtained. Fig.6 is another result of that analysis. It shows normalized displacement as a function of size of the motion mechanism. This result shows that a micro motion mechanism using piezoelectric element is able to move against high friction. A piezoelectric element makes very small displacement of several micrometers, but it has very fast response speed to compensate for it. As a result, it is able to generate sufficient impulsive force to move the

main body. The displacement of thermal expansion is roughly estimated as 2 or 3 micrometer with temperature rise of 10 degree, which is equivalent to piezoelectric element. Affordable force of the actuator using thermal expansion depends on the compliance of the actuating material. The following experiments show that the response speed is as fast as a piezo. A thermal expansion actuator has the same potential ability as a piezoelectric element.

#### THEORETICAL ANALYSIS

A theoretical estimation is carried out considering electric current heating and heat emission. The displacement of the actuator is supposed to be in proportion to the temperature rise and has no delay between the temperature rise.

$$\Delta\ell = \ell_0 \alpha T \quad (1)$$

The temperature distribution inside the wire is assumed to be uniform. Temperature of the actuator is calculated from the current discharge of the capacitor as follows:

$$T = \frac{CV_0^2}{2WK} (1 - e^{-\frac{2t}{RC}}) \quad (2)$$

( where  
 T:temperature rise  
 V<sub>0</sub>:driving voltage  
 K:specific heat  
 R:resistance of the wire  
 C:capacitance  
 W:weight  
 t:time )

The route of heat emission can be divided into radiation of infrared rays and conduction to surrounding air. The conduction does not exist when the mechanism in vacuum and depends largely on conditions. Only the radiation was taken into consideration for first approximation. The radiation rate is expressed as:

$$E_r(T) = \sigma(T^4 - T_e^4) \quad (3)$$

( where  
 E<sub>r</sub>:radiation per unit area and time  
 T: the temperature of the object  
 σ: radiation constant )

Combining (2) and (3) a differential equation about the temperature rise T can be obtained which expresses the displacement of the actuator.

$$\left\{ \begin{array}{l} \frac{dE(t)}{dt} = \frac{V_0^2}{R} e^{-\frac{2t}{RC}} - S\sigma(T^4 - T_e^4) \\ T = T_e + \frac{E(t)}{WK} \end{array} \right. \quad (4)$$

E is the energy given to the actuator and S is the surface area of the actuator. This equation is solved through numerical integration. Fig. 7 shows a result of the calculation. Upper figure shows the whole displacement of

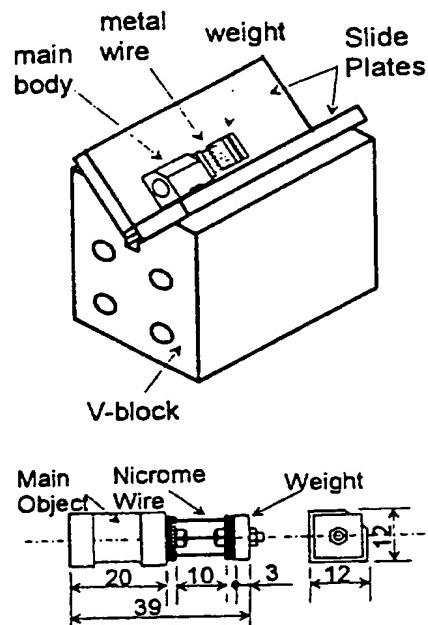
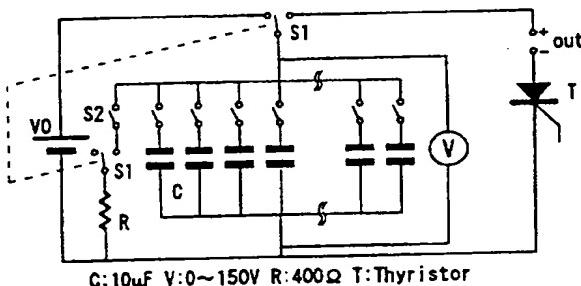


Fig.8 A schematic view of the experimental setup



C:10μF V:0~150V R:400Ω T:Thyristor

Fig.9 Driving circuit for heating the actuator

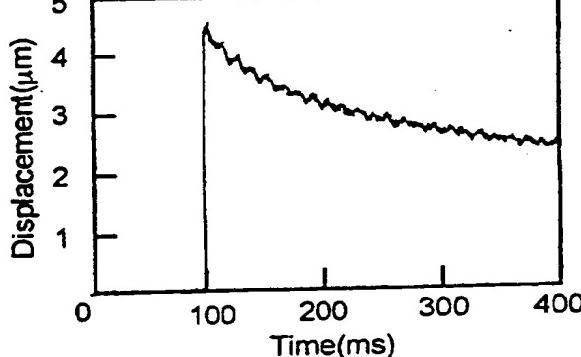


Fig. 10 Displacement of the actuator when main body is fixed ( V<sub>0</sub>=100(V), C=100μF, R=13Ω )

the actuator and lower figure (b) is the magnification of rising edge. The rise time is approximately 1 ms and is in good agreement with the experimental result. The fall time

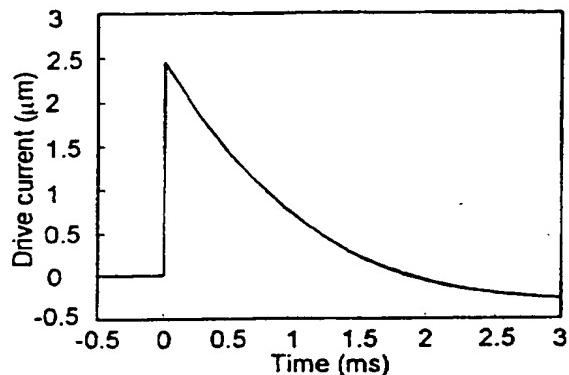


Fig. 11 Driving current of the actuator as a function of time ( $V_0=100\text{V}$ ,  $C=100\mu\text{F}$ ,  $R=13\Omega$ )

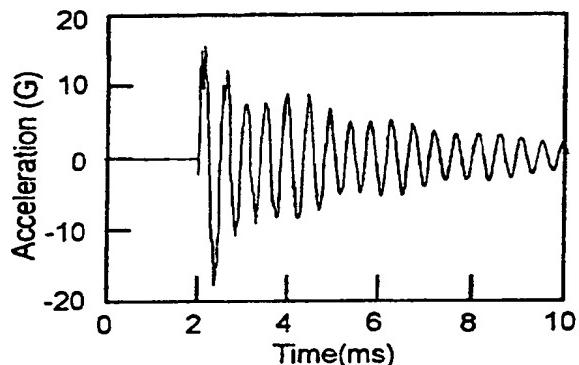


Fig. 12 Acceleration of the actuator  
( $V_0=100\text{V}$ ,  $C=100\mu\text{F}$ ,  $R=13\Omega$ )

is 0.2 second. This is much smaller than experiment. The temperature rise is approximately 30 deg.

## EXPERIMENTS

### Experimental setup

A basic experiment is carried out to check the characteristics of thermal expansion actuator. Fig. 8 shows the experimental setup. The main body is set on a 90° V-groove. The thermal expansion actuator is a 16 thread of Ni-Cr wire. The Diameter of the wire is 0.15mm. At the other end of the actuator, a weight is attached. The actuating part is heated through electric current. Fig. 9 shows the electric circuit for driving thermal expansion actuator. Electric charge is first stored in the capacitor and it is supplied to actuating part through thyristor in a short time to make rapid thermal expansion. Motion of the mechanism was measured by a gap sensor using optical fiber.

### Experimental results

The motion of thermal expansion actuator is measured to

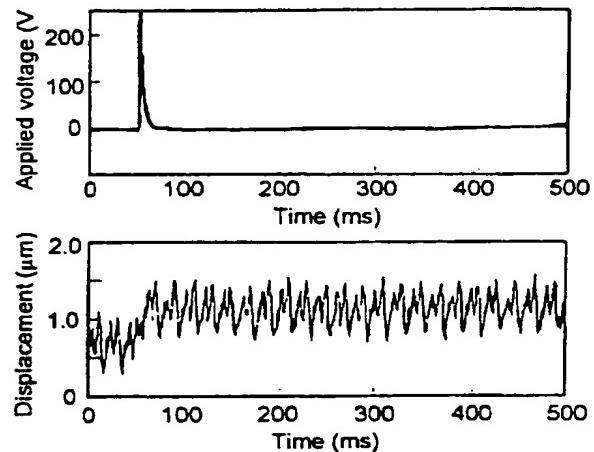


Fig. 13 Motion of the Impact Drive Mechanism using rapid thermal expansion (83 wire of 0.2mm dia.  $V_0=300\text{V}$ )

check the displacement and response speed. Fig. 10 shows a displacement of the actuator while the main body is rigidly fixed to the ground. The rising time of the displacement is as short as 1 millisecond and this is equal to the pulse width of the electric current of the driving circuit. Fig. 11 shows the wave form of the driving current of the actuator. This result implies that the response speed is as fast as the piezoelectric element and is sufficient for generating reactional force. The fall time of the displacement in the same figure is on the other hand, approximately 1 second. This is due to the low heat emission ratio of the actuator. Fig. 12 shows the acceleration of the rapid motion. It was measured by attaching an acceleration pick-up to the weight. The maximum acceleration is about 15G and it is equal to 0.2N multiplied by the mass of the weight. This is sufficient for driving the main body which weight is 10g. These results show that the thermal expansion is able to drive an Impact Drive Mechanism instead of piezoelectric element. Fig. 13 shows a displacement of a main body when it was operated on the principle of the Impact Drive Mechanism. This motion was measured using a 83 thread type actuator. The motion is about 0.5 $\mu\text{m}$ .

## CONCLUSION

A proposal is made for utilizing thermal expansion as an actuator for Impact Drive Mechanism. It has made sure that the displacement and the response speed of the thermal expansion are sufficient for generating impulsive inertial force to move the main body. The experiments were carried out with fundamental setup using electric

current heating method and the motion mechanism was able to move by rapid thermal expansion. The experimental setup appeared in this paper is not sufficiently small to verify the advantage of scale effect of thermal expansion. But the basic analysis shows that the smaller mechanism has faster response speed and high operating temperature has the same effect.

Several applications of the thermal expansion actuator will be possible taking the advantages of this actuator. One main application is medical field. This actuator is driven by thermal energy and it can be controlled by laser light through optical fiber. Electric current and voltage supply to an actuator may cause a trouble of an electric shock. The thermal expansion actuator is free from this danger and the actuator can be adopted for use inside the patients. A typical example is a fiber scope with micro manipulator used for micro surgery of digestive organs and blood vessels. Micro motion mechanisms in special environment are another field of application. Operation of micro mechanisms inside special chamber like vacuum, liquid and gas need remote energy supply. Laser lights and radio frequency electromagnetic wave can transport thermal energy without any connection.

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